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The Fate of Former Companions to Hypervelocity Stars Originating at the Galactic Center

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ABSTRACT

The hypervelocity star SDSS J090745.0+024507 in the halo of the Milky Way galaxy (Brown et al. 2005) most likely originated from the breakup of a binary star system by the central black hole, SgrA* (Hills 1988). We examine the fate of former binary companions to similar hypervelocity stars (HVSs) by simulating 600 different binary orbits around SgrA* with a direct N-body integration code. For some orbital parameters, the binary breakup process leads to HVSs with ejection velocities that are almost an order of magnitude larger than the velocity observed for SDSS J090745.0+024507. The former companion stars populate highly eccentric orbits which resemble the observed orbits for some of the stars nearest to SgrA*.

Key words: black hole physics-Galaxy:center-Galaxy:kinematics and dynamics-stellar dynamics

1 INTRODUCTION

Recently, the first hypervelocity star (HVS), SDSS J090745.0+024507, was discovered in the Galactic halo (Brown et al. 2005; Fuentes et al. 2005). This HVS is located at a heliocentric distance of $\sim$ 71 kpc and has radial velocity 853 ± 12 kms^{-1}. Its velocity is over twice that needed to escape the gravitational pull of the Milky Way. Hills (1988) was the first to recognize that a HVS might result from a close encounter between a tightly bound binary star system and the black hole at the Galactic center, SgrA*. Yu & Tremaine (2003) refined Hills' argument and added that HVSs might also be produced by three-body interactions between a star and a binary black hole. Because the existence of a second black hole in the Galactic center (Hansen & Milosavljević 2003) is only a hypothetical possibility (Schödel et al. 2003), we focus our discussion on the disruption of a tightly bound binary by a single supermassive black hole (SMBH).

The Keplerian orbits of massive stars within 10^2–10^4AU from the Galactic center provide strong evidence for the existence of a central SMBH with mass $\sim 4 \times 10^6 M_\odot$ (e.g. Ghez et al. 2005; Reid & Brunthaler 2004; Schödel et al. 2003). Since binaries are common in other star forming environments, it is only natural to explore the interaction between SgrA* and nearby binaries. Both Yu & Tremaine (2003) and Gould & Quillen (2003) describe instances where the tidal disruption of a binary by the SMBH leads to one star being ejected into close orbit around the black hole. Thus, it is only natural to ask: *Is it possible that some of these stars are former companions of HVSs?*

In §2 we describe the N-body code and simulation parameters that were adopted. In §3 we discuss our numerical results for the origin of the HVSs, and in §4 we compare the calculated orbits of the bound companion stars to the observed stellar orbits near the Galactic center. Our goal is not to cover the entire phase space of possible binary orbits but rather to examine whether some of the highly eccentric orbits of observed stars near SgrA* could have resulted with a reasonable probability from the disruption of a stellar binary.

2 COMPUTATIONAL METHOD

In our study we have used the N-body code NBODY0 written by Aarseth (1999), and presented in Binney & Tremaine (1987). We have tested NBODY0 against later versions of Aarseth's N-body codes (such as "triple"), and found the results to be identical to within the required precision. We adopted a small value of 10^{-8} for the accuracy parameter η, which determines the integration step through the relation $dt = \sqrt{\eta F/(d^2F/dt^2)}$ where dt is the timestep and F is the force. The softening parameter, *eps2*, which is used to create the softened point-mass potential, was set to zero. We treat

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the stars as point particles and ignore tidal and general relativistic effects on their orbits, since these effects are small at the distance ($\sim$ 10AU) where the binary is tidally disrupted by the SMBH.

We have set the mass of the SMBH to $M = 4 \times 10^6 M_\odot$ and the mass of each star to $m = 3M_\odot$, comparable to the estimated mass of SDSS J090745.0+024507 (Fuentes et al. 2005). All runs start with the center of the circular binary located 2000 AU ($= 10^{-2}$pc) away from the SMBH along the positive y-axis. This distance is comparable to the inner scale of the observed distribution of stars around SgrA* (Eckart & Genzel 1997; Schödel et al. 2003; Ghez et al. 2005), allowing the remaining star to populate this region after the ejection of its companion. This radius is also much larger than the binary size or the distance of closest approach necessary to obtain the relevant ejection velocity of HVSs, making the simulated orbits nearly parabolic. We used the same initial distance for all runs to make the comparison among them easier to interpret as we varied the distance of closest approach to the SMBH or the relative positions of the two stars within the binary.

We chose initial binary separations of $a = 0.05$ or 0.1AU because they provide ejection velocities in the range of interest[1] for the above parameters. Significantly wider binaries would give lower ejection velocities (Gualandris et al. 2005). Much tighter binaries would not be easily disrupted by the black hole, or may coalesce to make a single star before interacting with the SMBH. The size of a main sequence star of a few solar masses is $\sim$ 0.01AU, and so binaries tighter than $\sim$ 0.02AU are precluded because the two stars will develop a common envelope and eventually coalesce.

In the Galactic disk, about half of all stars form in binaries or small multiple systems (see e.g. Duquennoy & Mayor 1991), with roughly equal probability per logarithmic interval of separations, $dP/d\ln(a) = const$ (e.g. Abt 1983; Heacox 1998; Larson 2003). In the Galactic center environment, the maximum binary separation is limited by the tidal force of SgrA* at the distance d where the binary is formed (for conditions that enable star formation near the SMBH, see Milosavljević & Loeb 2004). Since the mass of the black hole is $\sim 10^6$ times larger than that of a star, this implies a maximum binary separation less than $(10^{-6})^{1/3} = 10^{-2}$ of the initial distance d. For $d = 2 \times 10^3$AU, the upper limit on the binary separation would be 20AU (or smaller if the tidal restriction applies during the formation process of the binary). If we assume a constant probability per $\ln(a)$ for $0.02 < a < 20$AU, then the probability of finding a binary in the range of $a = 0.05$–0.1AU is substantial, $\sim 10\%$.

We have found that the initial phase of the binary orbit plays a crucial role in the outcome. Therefore, we sampled cases with initial phase values of: -75, -60, -45, -30, -15, 0, 15, 30, 45, 60, 75, and 90 degrees. As initial conditions, we gave the binary system no radial velocity but a tangential velocity with an amplitude in the range between 5 and 500 km s^{-1} at the distance of 2000AU. As described analytically below, we expect no HVSs to be produced at larger tangential velocities. We ran 300 cases for each of the two binary separations, with a total of 600 simulations.

[1] Note that the original ejection speed of SDSS J090745.0+024507 should have been higher than its observed speed because of its deceleration in the Galactic potential.

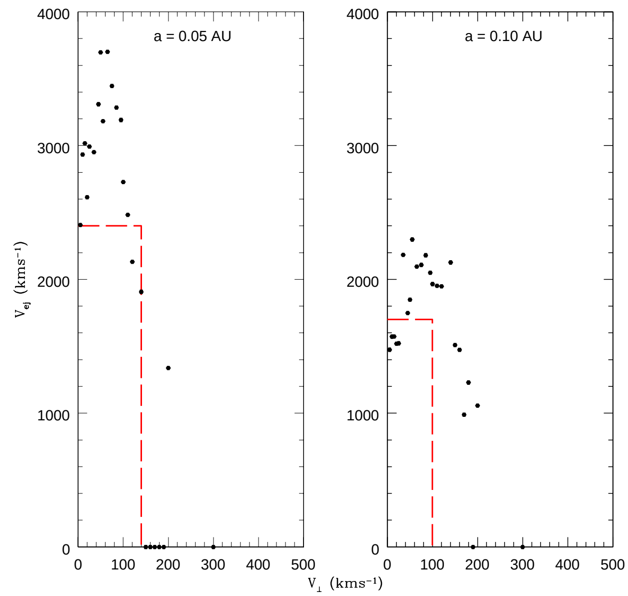

Figure 1. Ejection speed $v_{\rm ej}$ of the unbound HVS as a function of the initial tangential velocity $v_\perp$ of the binary at a distance of 2000 AU from SgrA*. The dashed line indicates the analytic model of Eqs. (4) and (3). Each point represents the average ejection velocity for all HVSs at the given tangential velocity (averaged over the initial orbital phase within the binary). The average value for $v_{\rm ej}$ over all points agrees closely with our analytical model. For $a = 0.05$ AU we get agreement within 16%, and for a = 0.10 AU we get agreement within 3%.

3 ORIGIN OF THE HYPERVELOCITY STAR

Given a binary system with stars of equal mass m separated by a distance a and a SMBH of mass $M \gg m$ at a distance b from the binary, tidal disruption would occur if $b \lesssim b_{\rm t}$ where

$$\frac{m}{a^3} \sim \frac{M}{b_{\rm t}^3} \tag{1}$$

The distance of closest approach in the initial plunge of the binary towards the SMBH can be obtained by angular momentum conservation from its initial transverse speed $v_\perp$ at its initial distance from the SMBH, d,

$$v_\perp d = \left(\frac{GM}{b}\right)^{1/2} b. \tag{2}$$

The binary will be tidally disrupted if its initial transverse speed is lower than some critical value,

$$v_\perp \lesssim v_{\perp,\rm crit} \equiv \frac{(GMa)^{1/2}}{d}\left(\frac{M}{m}\right)^{1/6} = 10^2 \frac{a_{-1}^{1/2}}{m_{0.5}^{1/6} d_{3.3}} \ {\rm km\ s^{-1}}, \tag{3}$$

where $a_{-1} \equiv (a/0.1$ AU), $d_{3.3} = (d/2000$ AU), $m_{0.5} \equiv (m/3M_\odot)$, and we have adopted $M = 4 \times 10^6 M_\odot$. For $v_\perp \lesssim v_{\perp,\rm crit}$, one of the stars receives sufficient kinetic energy to become unbound, while the second star is kicked

into a tighter orbit around the SMBH. The ejection speed $v_{\rm ej}$ of the unbound star can be obtained by considering the change in its kinetic energy $\sim v\delta v$ as it acquires a velocity shift of order the binary orbital speed $\delta v \sim \sqrt{Gm/a}$ during the disruption process of the binary at a distance $\sim b_t$ from the SMBH when the binary center-of-mass speed is $v \sim \sqrt{GM/b_t}$ (Hills 1988; Yu & Tremaine 2003). At later times, the binary stars separate and move independently relative to the SMBH, each with its own orbital energy. For $v \lesssim v_{\perp,\rm crit}$, we therefore expect

$$v_{\rm ej} \sim \left[\left(\frac{Gm}{a}\right)^{1/2}\left(\frac{GM}{b_{\rm t}}\right)^{1/2}\right]^{1/2} = 1.7\times 10^3 m_{0.5}^{1/3} a_{-1}^{-1/2}\ {\rm km\ s^{-1}}. \quad (4)$$

Figure 1 compares the above approximate model (dashed line) with the results from our N-body simulations (points). The expected values of $v_{\rm ej}$ and $v_{\perp,\rm crit}$ (dashed line) and their dependence on the binary separation a in Eq. (3), are consistent with our numerical results. However, statistical variations exist. For $v_\perp \lesssim v_{\perp,\rm crit}$ the numerical runs show variations by up to a factor of ~ 2 around the expected flat value of $v_{\rm ej}$ in Eq. (4). There are also exceptions of escaping stars with $v_\perp \gtrsim 200$ kms^{-1}.

Hills (1988) concluded that the ejection speed of a HVS could reach a value of ~ 4000 km s^{-1}. Although the vast majority of our simulated HVSs did not go beyond Hills' limit, there were a few exceptions (see Figure 2). Of our 600 runs, there were 307 stars that escaped the SMBH, and of those 12 had velocity $\geqslant 4000$ kms^{-1}. Furthermore, 3 had $v_{ej} \gtrsim 6000$ kms^{-1}, of which the largest had velocity $v_{ej} = 7073$ kms^{-1}. The likelihood of observing such a HVS is remote. As noted, HVSs with $v_{ej} \geqslant 4000$ kms^{-1} rarely occur, and moreover a star with velocity 6000 kms^{-1} would traverse the ~ 200 kpc scale of the Milky Way halo (Wilkinson & Evans 1999) in just 30 million years, reducing the likelihood for the observer to find it.

4 FATE OF THE COMPANION STAR

The orbits of a number of known stars around Sgr A* have been studied in detail (see e.g. Eckart & Genzel 1997; Schödel et al. 2003; Ghez et al. 2005). An intriguing question is how did some of these stars obtain their highly eccentric orbits near the central SMBH.

Figure 3 shows the orbits of the companion stars for five HVSs produced by our simulations. All of the orbits have very high eccentricities, ranging from $e = 0.966$ to $e = 0.999$. Similar results are obtained for other orbits, not shown in the figure. Previously derived constraints on HVS J090745.0+024507 (Fuentes et al. 2005) indicated that its former companion must have remained bound to SgrA* with an eccentricity within the range $e = 0.97$ to $e \sim 1$, in agreement with our results.

Ghez et al. (2005) list stellar orbital parameters for seven stars near SgrA*. All but one of the stars have high eccentricity, and in particular, S0-16 has a well defined eccentricity of 0.974 ± 0.016. It has a semimajor axis $a = 1680 \pm 510$ AU, and period $P = 36 \pm 17$ years. Our runs produce a smaller semimajor axis and period, with $a \sim 400$ AU and $P \sim 4$ years, but these numbers can be changed by varying the stellar masses (see the bottom right panel of Fig. 3) or the initial binary eccentricity. Schödel et al. 2003 provide the eccentricity of six stars; of particular interest are S14 (=SO-16) and S8 (=SO-4) with high eccentricities of 0.97 and 0.98 respectively. The estimated periods are 69 years and 342 years for semimajor axes of 3115 AU and 5982 AU, respectively. For S0-2, Ghez et al. (2005) provided a period of 14.53 years and a semimajor axis of 919 AU, with an estimated eccentricity of 0.8670, which is not within the range of our runs but close. Gould & Quillen (2003) suggested that the tidal disruption of a massive-star binary could account for the orbit of star S0-2. If so, a star of order 100 $M_\odot$ must be the companion. Although possible, such an association is unlikely given the rarity of expected companion stars with this mass (see Kroupa 2005). Stars on an eccentric orbit may also be produced through an exchange reaction of a massive star with a stellar-mass black hole on a tight orbit around SgrA* (Alexander & Livio 2004).

Owing to the flux limit inherent in infrared observations of the Galactic center, the observed close-in stars near SgrA* are more massive than we assumed in our analysis. For example, Ghez et al. (2003) estimated a mass of $\sim 10 M_\odot$ for S0-2. An opposite selection effect applies to SDSS J090745.0+024507, because stars with a mass $\gtrsim 10M_\odot$ would not be observable in the Galactic halo as their lifetime would be shorter than the duration of their journey. The scaling in Eq. (4) implies only a modest change in $v_{\rm ej}$ for $10M_\odot$ stars. As an example, the bottom right panel of Figure 3 shows the outcome of the disruption process of a tight ($a = 0.2$AU) binary containing stars of $10M_\odot$ and $3M_\odot$. The $3M_\odot$ star is ejected while the $10M_\odot$ companion remains in a highly eccentric orbit with $e = 0.999$. The orbital semimajor axis is 700 AU, and the period is 9.3 years. A different run with a 0.4AU binary starting at 4000 AU with a transverse speed of 5 km s^{-1} left the $10M_\odot$ companion with an orbital semimajor axis of 1430 AU and an eccentricity of $e = 0.99$, closer to the observed parameters of S14.

What is the likelihood for a collision between the stars as a result of the kick they acquire from their interaction with the SMBH? In our runs, the binary was taken to lie in the same plane as its orbit around the SMBH. Assuming that the impulsive kick is given by the SMBH towards a random direction within this plane, the probability for a collision in a case that otherwise would have produced a HVS is four time the radius of a star (which is ~ 0.01 AU for a $3M_\odot$ star) divided by the circumference of a circle with a radius equal to the binary separation. For $a = 0.05$AU and 0.1 AU this would imply a collision probability of 12.73% and 6.37%, respectively. Our runs gave consistent statistical results, with a collision fraction among HVS orbits of $\sim 7.7 \pm 2.1\%$ for $a = 0.05$AU and $5.6 \pm 1.9\%$ for $a = 0.1$AU. The likelihood for a collision is expected to be smaller in the more general case when the binary lies in a different plane than its orbit around the SMBH. Averaging over all random orientations, the collision probability is $[\pi(0.02AU)^2/4\pi(0.05AU)^2] = 4\%$ for $a = 0.05$AU and 1% for $a = 0.1$AU. The small likelihood introduces only a minor correction to our earlier statistical results (which were obtained by approximating the stars as point-like particles). An example of an orbit that leads to a collision is shown in the top-right panel of Figure 3.

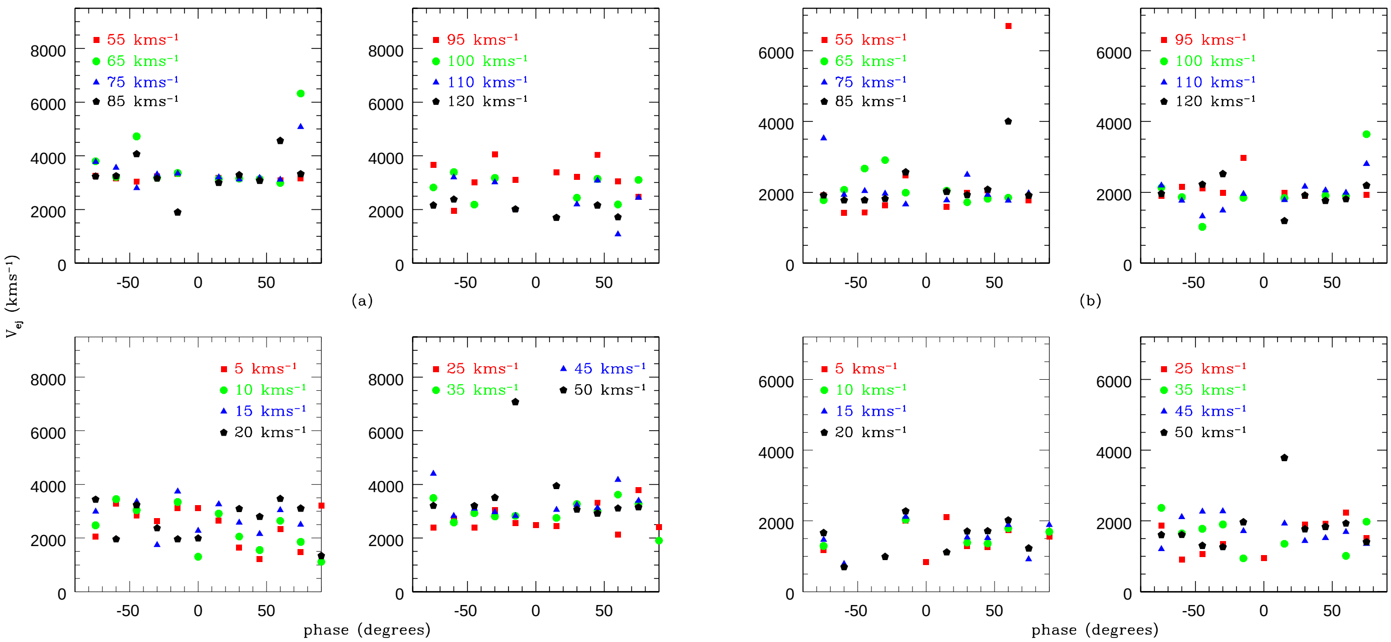

Figure 2. Ejection speed $v_{\rm ej}$ as a function of initial orbital phase within the binary (in degrees). The four cases in (a) refer to a binary separation $a = 0.05$ AU. The cases in (b) refer to $a = 0.1$ AU. The ejection velocity tends to lie within the range of 2000–4000 km s^{-1}, but occasionally goes beyond it. The ejection speed is sensitive to the orientation of the binary when it gets disrupted, which in turn depends on the initial phase as well as the other (internal and bulk) orbital parameters of the binary. The different point types refer to different choices for the transverse speed of the binary relative to the SMBH at their initial separation of 2000AU.

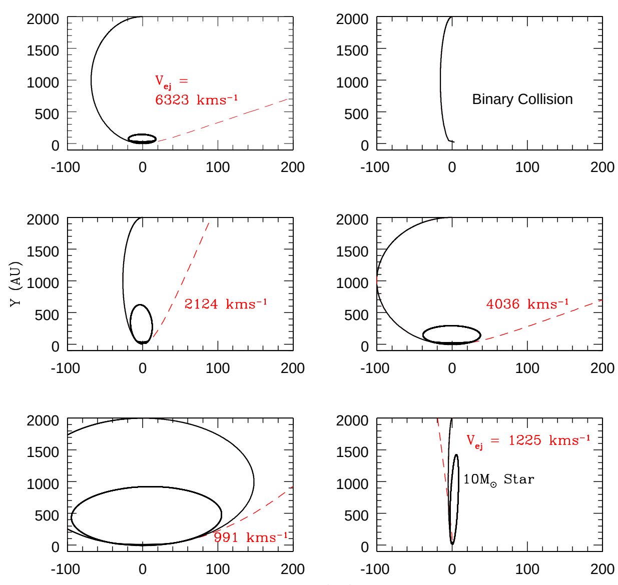

Figure 3. Orbits of the former companions to HVSs. The SMBH is located at the origin, and the binary system is given an initial tangential velocity $v_\perp$ along the negative x-axis at an initial distance of 2000 AU along the positive y-axis. The escape trajectory of the HVS is delineated by the dashed line. The binary is often disrupted upon its first revolution around the black hole as seen in the bottom right and middle two plots. However, sometimes it takes an extra revolution as seen in the other cases. This is most likely caused by the changing phase of the binary at closest approach. Note that the x and y axis have different label scales. The top right panel shows the orbit of the binary system until collision. The bottom right panel shows a $10M_\odot$ star and a $3M_\odot$ companion with initial orbital separation of $a = 0.2$ AU. In all other cases both stars were $3M_\odot$ and had orbital separation $a = 0.05$ AU.

The two stars would not merge as a result of the collision if their relative speed significantly exceeds the escape speed from their surface (~ 500 km s^{-1}). In the example shown, the relative speed of the stars at impact was 666 km s^{-1}. Grazing-incidence collisions, which are more probable than head-on collisions, may lead to HVSs which are rapidly spinning (Alexander & Kumar 2001).

Finally, we note that for the typical impact parameter that leads to the break-up of the binary with $a \sim 0.05$AU by the black hole (Eq. 1), the tidal force on a star is less than a few percent of the gravitational force that binds the star; however, some rare encounters (with a replaced by the stellar radius in Eq. 1) may lead to the tidal disruption of the stars.

5 CONCLUSIONS

Our N-body simulations indicate that tight binaries with separations 0.05–0.1AU which approach within a distance $\lesssim 10$AU from SgrA* could produce HVSs with velocities almost an order of magnitude greater than the observed velocity of HVS SDSS J090745.0+024507. The orientation of the binary at closest approach plays an important role in determining whether the binary is tidally disrupted by the SMBH and what is the eventual ejection velocity of the unbound star in that case (see Fig. 2). The phase sensitivity originates from the fact that the crossing time of the distance at which tidal disruption occurs, $(GM/b^3)^{-1/2}$ is shorter than the binary orbital time $\sqrt{2} * pi * (Gm/a^3)^{-1/2}$. Numerically, we have not been able to identify a simple trend for the phase angle at the breakup radius that would appear more organized than the results in Figure 2.

The former companion star to a HVS is typically kicked into a highly eccentric orbit with an eccentricity $\geqslant 0.966$ (see Fig. 3). The resulting eccentricity is similar to that observed for a number of stars near the Galactic center such as S8 ($e = 0.98$) and S14 ($e = 0.97$), suggesting a possible binary origin for these stars.

Surveys of HVSs in the halo of the Milky Way galaxy select moderate-mass ($m \lesssim 5M_\odot$) stars with lifetimes longer than their travel times ($\gtrsim 10^8$ years) while infrared surveys of the vicinity of SgrA* select for bright massive stars ($m \gtrsim 10M_\odot$) with short lifetimes ($\lesssim 10^7$years). The findings of existing surveys suggest that both populations of stars coexist. Future extensions of this work may examine a larger set of binaries with various stellar masses and internal orbital eccentricity.

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REFERENCES

Aarseth S. J., 1999, PASP, 111, 1333
Abt H. A., 1983, ARAA, 21, 343
Alexander T., Kumar P., 2001, ApJ, 549, 948
Alexander T., Livio M., 2004, ApJL, 606, L21
Binney J., Tremaine S., 1987, Galactic Dynamics. Princeton University Press, Princeton, NJ
Brown R. J., Geller M., Kenyon S., Kurtz M., 2005, ApJL, 622, L33
Duquennoy A., Mayor M., 1991, A&A, 248, 485
Eckart A., Genzel R., 1997, MNRAS, 284, 576
Fuentes C., Stanek K., Gaudi B., McLeod B., Bogdanov S., Hartman J., Hickox R., Holman M., 2005, ApJL, submitted (astro-ph/0507520)
Ghez A., Duchêne G., Matthews K., Hornstein S., Tanner A., Larkin J., Morris M., Becklin E., Salim S., Kremenek T., Thompson D., Soifer B., Neugebauer G., McLean I., 2003, ApJL, 586, L127
Ghez A., Salim S., Hornstein S., Tanner A., Lu J., Morris M., Becklin E., Duchêne G., 2005, ApJ, 620, 744
Gould A., Quillen A., 2003, ApJ, 592, 935
Gualandris A., Portegies Zwart S., Sipior M., 2005, MNRAS, 363, 223
Hansen B., Milosavljević M., 2003, ApJL, 593, L77
Heacox W., 1998, AJ, 115, 325
Hills J., 1988, Nature, 331, 687
Kroupa P., 2005, Nature, 434, 192
Larson R., 2003, Rep. Prog. Phys., 66, 1651
Milosavljević M., Loeb A., 2004, ApJL, 604, L45
Reid M., Brunthaler A., 2004, ApJ, 616, 872
Schödel R., Ott T., Genzel R., Eckart A., Mouawad N., Alexander T., 2003, ApJ, 596, 1015
Wilkinson M., Evans N., 1999, MNRAS, 310, 645
Yu Q., Tremaine S., 2003, ApJ, 599, 1129

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